Moisture Sensor Technology-A Summary of Techniques for Measuring Moisture Levels in Building Envelopes

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ABSTRACT

As moisture-related problems increase in homes, the need for sensors to accurately measure the moisture level in the building envelope grows. Sensors are needed to assist in model verification, to indicate the effectiveness of moisture abatement steps, and to warn of potential moisture intrusion. The most popular sensors currently used by building scientists are those based on electrical resistance, but a great deal of dissatisfaction exists with this technique. Installation of these sensors is difficult, drift in the response causes transient changes in the measurements, and calibration has proven to be a challenge. Numerous techniques promise better accuracy and easier use than the electric resistance probes, but work is needed to produce a sensor small enough to fit unobtrusively in a wall cavity. This work has identified many existing techniques for measuring moisture and presents advantages and disadvantages of each.

INTRODUCTION

Building practitioners have a significant need for in situ moisture content sensors to help alleviate the problems associated with excess moisture accumulation in buildings. Such problems can lead to mold and mildew growth, structural decay, loss of thermal integrity, and pest infestation. Numerous theoretical models have been proposed to predict the transfer of moisture in buildings, and accurate sensors are needed as a research tool to verify the results of these models, especially when new types of construction or materials are proposed. Sensors are also necessary as a field tool to judge the effectiveness of moisture abatement steps taken in structures. The ultimate use for moisture sensors would be as a predictive tool in a "smart" home that would indicate moisture anomalies so that adjustments could be made to the heating and ventilation systems or repairs could be made to prevent any further problems.

The term "moisture content" refers to the amount of water present in a solid material. The amount of water present in air, on the other hand, is indicated by such quantities as the relative humidity, humidity ratio, or partial pressure of water vapor. The standard test method for measuring the moisture content of wood is documented in ASTM D 4442 (ASTM 1992) and ISO 12570 (ISO 2000) and is representative of a typical method for all building materials. In this method, the weight of the specimen at the moisture content of interest is compared to the weight of the specimen after it has been dried in an oven. The moisture content is given by the relation,

$$MC = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100\,, \qquad (1)$$

where

MC = moisture content in percent,

W_{wet} = mass of the specimen before drying,

W_{dry} = mass of the dry specimen.

The wood specimen is placed in an oven maintained at 103°C ± 2°C. At higher temperatures, it is believed that constituents other than moisture will be driven from the specimen, thereby changing the dry mass of the material and providing a biased estimate of the moisture content of the specimen. For other building materials, lower temperatures may be necessary because of changes to the structure of the material at 103°C. For example, ISO 12570 suggests a drying temperature of 70°C ± 2°C for some cellular plastics and a drying temperature of 40°C ± 2°C for materials in which water

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of crystallization is driven out at 105°C, e.g., gypsum. ASTM C 472 (ASTM 1999) also addresses drying of gypsum and gypsum plasters and recommends a drying temperature of 45°C ± 3°C. For moisture content measurements, ASTM estimates that the precision can be no greater than ±1% MC using the procedure unless specimen variability and oven variability are examined. ISO estimates the accuracy to be no greater than 3% of the true value (i.e., the error between the measured value and the actual value divided by the actual value is within 3%). A modification to the oven drying technique that is not mentioned in the ASTM document but that has been employed by researchers is the use of desiccant in place of an oven for drying (Richards et al. 1992; Thomas and Burch 1990). Some disagreement exists as to whether oven-drying removes volatile compounds other than water, even at the temperatures specified in the ASTM standard. For this reason, some (Richards et al. 1992; Thomas and Burch 1990) have placed the specimen in a desiccating jar to remove the water. The use of desiccation, however, raises questions as to whether all of the water is removed from the specimen. The relative humidity in a jar with calcium chloride as the desiccant is 1.4% (Thomas and Burch 1990). Though this value is quite low, water is not completely eliminated from the air surrounding the sample and, hence, moisture can still be present in the solid at equilibrium conditions.

An in situ moisture sensor for building envelopes has several requirements. First, as with any sensor, it must be nonintrusive. For applications inside a wall cavity, this requirement calls for sensors that are very small so that the construction is not altered and moisture transfer is not affected by the sensor. Remote readings of these in situ sensors are necessary because it is not practical to remove sections of construction to get to the sensor. Leads will be needed from the sensor to the central monitoring location unless wireless transmission capabilities are incorporated into the system. The leads should be small so that the construction is not affected and durable so that neither damage during installation nor degradation over time occurs. The ideal sensor system should be totally automated to remove the tedious task of manually taking readings from each sensor. To accomplish this task, the sensor should be capable of being incorporated in a multiplexing system. Low cost per sensor will be vital in sensor development as many measurement points are needed throughout a building. Since moisture problems can arise in many areas of a building envelope, an array of sensors will be needed to diagnose any unwanted moisture intrusion. The large number of sensors needed per application would eliminate any sensors that have a high cost per sensor. Finally, the ideal sensor needs to be durable, as most applications will require the sensor to be embedded in a structure for a period of at least one year. Sensors embedded in a wired house would need to be durable for the operational life of the home. In such an application, an added benefit would be the ability to easily replace sensors that malfunction.

While these requirements seem severe, other parameters of the measurement system are less restrictive. Because moisture transport in buildings is a relatively slow process, rapid data acquisition is not a priority. Typical rates of measurement will be no greater than one per hour. Since the measurement rate is small, the sensor system will yield a manageable amount of data, and real-time data processing is not a necessity. The environmental conditions that the sensor will face are relatively benign compared to conditions that many sensors face in industrial applications. Temperatures are limited to a range of approximately −30°C to 45°C, and pressures will be near atmospheric pressure. These conditions will not require any special materials or packaging that might be necessary if the sensor were to operate at elevated temperatures, cryogenic temperatures, vacuum, or high pressures. It is also expected that the sensor will not experience any significantly corrosive chemicals in a building, though moisture itself may lead to corrosion. So, while the restrictions for a sensor may seem significant, the situation could be worse given a different physical environment.

In evaluating moisture problems in buildings, measurements of both the moisture content of the solid and the humidity surrounding the material are useful. Moisture content can be used to indicate the potential for structural degradation and loss of thermal integrity, whereas humidity is often the best indicator of the potential for biological growth on the surface of a material. The two quantities are intimately related because a high humidity in the air surrounding a solid will tend to lead to higher moisture contents in the solid. Because of the difficulty in accurately measuring the moisture content of a solid, researchers have often used measurements of humidity in place of moisture content measurements. Functional relationships can be used to translate these humidity measurements to moisture content. While details of these techniques will be presented later, it should be noted that humidity measurements in themselves are more appropriate for certain uses than moisture content measurements. For example, the International Energy Agency published guidelines that suggest that the surface relative humidity levels should be maintained below 80% on a monthly mean basis to prevent mold growth (IEA 1990). To properly develop instrumentation to prevent moisture problems in buildings, development of improved moisture content sensors for solids should be accompanied by efforts to develop improved humidity sensors for monitoring the potential for biological growth on wall surfaces and at critical interfaces within a building envelope.

Two key reviews of techniques to measure moisture in building envelopes have previously been published. Whiting (1983) provided an in-depth discussion of the available techniques for measuring both the moisture content of solid materials and for measuring humidity as it pertains to building construction. The author concluded that instrumentation for measuring the moisture content was insufficient, and the most promising techniques involved the use of electrical capacitance and nuclear magnetic resonance. TenWolde and Courville (1985) also reviewed instrumentation for measuring moisture in building envelopes. They commented that more knowledge was needed of the actual performance of instrumentation in buildings. The purpose of the present discussion is to expand upon these works and indicate changes that may have occurred since the mid-1980s. Surprisingly, many of the methods that were used at that time are still the predominant means of measuring moisture today. While the building science community has not adopted many new techniques, other industries have continued to develop moisture measurement techniques. Food processing, paper manufacturing, and materials processing are only a few examples of the industries that require thorough knowledge of the moisture content of solids. Wang (2000) recently described different technologies that are prevalent for measuring the moisture content in ceramics. Some of these ideas may be applicable to in situ moisture measurement in building envelopes. The following discussion describes several techniques that are currently used to make in situ measurements of moisture or that could possibly be incorporated in sensors of the future. Table 1 summarizes the advantages and disadvantages of all of the techniques that are discussed.

MOISTURE MEASUREMENT TECHNIQUES

Gravimetric Plugs

As mentioned previously, the most direct way to measure moisture content is through gravimetric means. Numerous researchers have incorporated this technique in studies. The technique typically involves insertion of removable plugs that are periodically taken out of the wall. These plugs are weighed immediately upon removal and are then placed in an oven to dry, as specified in ASTM D 4442. Alternatively, the dry mass can be obtained before the test begins so that oven drying is not needed for each measurement. Through the use of Equation 1, the moisture content of the material is determined. The plugs are then reinserted into the wall. The works of Burch et al. (1979), Ojanen and Simonson (1995), and Tobiasson et al. (1977) give examples of studies in which gravimetric methods are used to measure moisture content of a material in situ.

The advantage of this technique is that it is a direct measure of the moisture content. If the prescribed methods are followed, the accuracy is excellent, and repeatability is not a concern. The method has some severe drawbacks, however, for making in situ measurements. First, the method is inherently destructive. Cores of material must be drilled into the wall assembly, thus damaging the construction at the numerous measurement locations. Another major drawback of this approach is that it is very labor intensive. To date, no examples of automating this task are evident. The only obvious method of automation would require robotics, and such a technique is not practical in most situations. A third disadvantage of this method is the uncertainty in moisture transport due to the lack of continuity in the material. A gap exists between the surrounding material and the plug, and the fit between the two will likely degrade as the plug is removed and reinserted. Does this gap change the moisture performance of the wall? For example, does the gap provide a channel for liquid water to flow? Does the gap minimize capillary transfer from the wall to the plug? In addition to compromising the hygrothermal integrity of the wall, these factors may result in the moisture content of the sensor being different from that of the surrounding material.

Thermal Capacitance

The presence of water in a material will change its thermal transmission and storage properties. Simpson and TenWolde (1999) give relations for the thermal conductivity (k) and heat capacity (c_p) of wood as a function of moisture content. These equations indicate that k increases linearly with moisture content, while heat capacity increases with moisture content according to a more complex formula. These changes in properties can be used to indicate the moisture content of a material. Dougherty and Thomas (1992) describe an in situ measurement of the thermal conductivity and thermal diffusivity of insulation that uses a self-heating thermistor. The thermistor inputs a short pulse of heat into the material and then measures the transient decay of the temperature. This transient profile can be used to determine both properties according to the model of Balasubramaniam and Bowman (1977). Woodbury and Thomas (1985) used this technique to measure the thermal conductivity of wet insulation. Before these works, Hagemaier (1970) measured the heat capacity of insulation to determine its moisture content by placing a thermocouple on its surface and flashing the specimen with infrared heating.

These techniques can be easily applied to in situ measurements since the instrumentation is small and affordable. Questions of accuracy arise, as Dougherty and Thomas found large uncertainties in their measurements depending upon the calibration of the instruments and the packaging of the thermistors. Other techniques for measuring these properties in situ may provide better means of determining the moisture content.

Electrical Resistance

The most popular technique for determining the moisture content of building materials is through measurements of the electrical resistance of the material. Dry wood, for example, has a very high electrical resistance, but the addition of water to wood drastically decreases the resistance. By creating a simple DC circuit that includes the material of interest, that resistance can easily be measured by common equipment. Many commercially available probes utilize this property of building materials to provide the moisture content. These instruments were first described by James (1963), and their use is described in ASTM D 4444 (ASTM 1992).

The dependence of the electrical resistance of wood with moisture content can be modeled with a relationship provided by Carll and TenWolde (1996). They found that the logarithm

TABLE 1
Summary of Moisture Content Sensor Technologies

Technology	Advantages	Disadvantages
Gravimetric plugs	Direct means of measuring MC Accurate and repeatable	Labor intensive – not conducive to automation Destructive measurement Lack of continuity in wall
Thermal capacitance	Simple and affordable Simple installation	Questionable accuracy Nonlinear relationship between moisture and thermal diffusivity
Electrical resistance	Significant sensitivity of resistance to MC Simple instrumentation Low cost	Severe sensor to sensor variability Requires in situ calibrations for greatest accuracy Changes in contact between sensor and material over time affects measurement Electrical interference Destructive (pin-probes)
Dielectric property measurements	Good sensitivity of material capacitance to MC Simple electronics Nondestructive probes	Distributed measurement location Susceptibility to electrical noise
Infrared techniques	Noncontact measurement Accurate Insensitive to electrical noise	Surface measurement – unable to detect MC below surface, excess surface moisture skews results Aging of surface could change reflectance independent of MC Expensive Challenge of multiplexing
Microwave	Accuracy Affordability of components Nondestructive	Difficult to construct Distributed measurement
Nuclear magnetic resonance	Accurate Direct detection of water Can differentiate between different states of water	Cost Size – difficult to develop small in situ probes
Nuclear scattering	Direct detection of water	Safety Packaging for in situ sensor Cost Resolution
Humidity sensing	Existing technology Small sensors Indicator of mold growth potential	Drift Uncertainty in sorption isotherm Instability at high RH Small errors in RH lead to large errors in MC at high MC.

of the resistance is linearly dependent with the logarithm of moisture content. The resistance is also dependent upon the temperature, so temperature corrections are needed to properly estimate the moisture content from resistance measurements. In addition to the temperature dependence, the resistance will depend upon the wood species and the direction relative to the grain. The resistance parallel to the grain is approximately half that across the grain (Simpson and TenWolde 1999). The technique can typically be used for moisture contents ranging from approximately 6% up to the fiber saturation point.

Commercially available probes of this variety typically use two metal pins as electrodes that are driven into a material. If the pin is insulated up to its tip, then the resistance measured is that across a direct line between the tips of the two pins. By inserting the pins to different depths, one can obtain the moisture profile at different locations within the material. If the pins are not insulated, however, the resistance measured will be the lowest resistance between the two shafts making up the pins. A problem could occur, for example, if the surface moisture level is significantly higher than the moisture content within the material. In this case, the surface moisture would lead to an erroneous elevated reading.

A typical use of these probes is described in Tsongas and Nelson (1991). Other researchers have made their own sensors by attaching electrodes to a material with electrically conducting epoxy (Burch et al. 1995; Zarr et al. 1995; Rode and Burch 1995). At the conclusion of their tests, Zarr et al. (1995) checked all sensors in a chamber of fixed humidity and found that variability between sensors was quite large before calibration corrections were applied. In 23 sensors tested on sugar pine samples inserted in a chamber of fixed relative humidity, the standard deviation of these measurements was as high as 2.62% MC over the range studied, with the standard deviations increasing with moisture content. Cleary (1985) created custom-made pin probes by hammering silver-plated nails into wood members and attaching an ohm-meter to these probes. The resistance technique was also used by Samuelson (1991) to measure the presence of moisture on a surface. In this work, two wires were set in paint parallel to each other, and the resistance between these wires indicated the presence of moisture.

A variant of this type of sensor is the so-called "Duff" probe, or matchstick probe, initially described by Duff (1966). Metal electrodes are attached to opposite faces of a small block of wood. The resistance of this piece of wood is monitored after it is placed in a building cavity. By matching the wood in the sensor to the wood in the building cavity, the sensor's moisture content will closely match that of the material of interest. Duff claims an accuracy within 1% MC, but that value was obtained after eliminating sensors that were deemed to be inaccurate. The sensor can also be used as a humidity measuring device owing to the relationship described by the sorption isotherm. The accuracy of this probe for measuring relative humidity was discussed by Carll and TenWolde (1996). They found that the error can be limited to ±10% relative humidity with careful calibration, a rather large error compared to other relative humidity sensors. Two studies that have used the matchstick probes are those by Harrje et al. (1985) and Rose (1992).

The electrical resistance method is the predominant means of measuring the moisture content in building materials because of the significant sensitivity of resistance to moisture, the low cost of the instruments, and the simplicity in using the method. Problems have arisen with this technique, however. Repeatability between sensors has been poor, often leading to the requirement that in situ calibrations be carried out to ensure accurate results. Other problems that have occurred relate to the electrical nature of the measurements. Voltages from other sources, including other measurement devices, could disrupt the signal from the moisture sensor. Noise can also be picked up readily in the long wires needed to transmit the resistance values from the measurement location. Over time, the stability of the measurements is also in question because of physical changes in the material and the probe. Contact between the sensor and the material can change over time, and changes in the distribution of salts in the material will change the resistance independently of moisture content.

Dielectric Properties

The other popular method for measuring the moisture content in building envelopes involves the electrical capacitance or dielectric constant of the building material (the dielectric constant is the ratio of the capacitance of the material to the capacitance of vacuum). The capacitance of water is from 10 to 30 times as great as that of wood, so its presence will affect the overall capacitance of the material. Numerous hand-held meters are commercially available that use this property to estimate the moisture content in a nondestructive manner. The meter typically consists of two pads that are placed against the wall. The material in the wall forms a capacitor in a circuit between the pads that is highly sensitive to the moisture content of the material. Such a probe can provide rough estimates of the moisture content, but it cannot be used to pinpoint the moisture content at a particular location because the measurement location is not precise. All materials in the vicinity of the sensor will affect the reading, so it is difficult to pinpoint the exact source of a high or low measurement. Factors such as surface moisture can disturb the reading, so readings of the moisture content of interior components of the wall are prone to significant error. Knab et al. (1981) reviewed these sensors and found that their accuracy for measuring moisture content was low compared to those of infrared sensors and nuclear sensors. Capacitance meters, however, are very useful in detecting serious moisture problems such as leaks in walls and roofs.

Some researchers have attempted to create an in situ sensor based on the capacitance of the material. Courville et al. (1989) made a probe with two parallel rows of 12 pins each that could be inserted into a material. The capacitance across these rows was measured to determine the moisture content of insulation; the researchers estimate that the probe can measure moisture contents up to 30% volume fraction for fiberglass and 40% volume fraction for phenolic foam with an uncertainty of 10%. In this work, Courville et al. also discuss a method to use embedded thermocouples to measure the capacitance in the material. In this technique, the thermocouples can be used both for temperature measurements and for moisture measurements. Cunningham (1986) devised a combination moisture sensor for wood that measured capacitance when moisture contents were above 25% and measured electric resistance for moisture contents below 30%. In the region where capacitance is the sole method of measurement, the wood is likely beyond the fiber saturation point. This study suggests that the capacitance method is not as effective below fiber saturation since the resistance method was used predominantly in that region. Eller and Denoth (1996) and Valente et al. (1998) also describe in situ capacitive sensors that were used to measure the moisture content of soil and wheat.

Another technique that utilizes the shift in the dielectric constant of a material with moisture is time domain reflectometry (TDR). In this technique, an electrical pulse is sent down a metal rod and reflects back when it reaches the end of the rod. The travel time of the pulse is dependent upon the capacitance of the surrounding material. By embedding this probe into the material of interest, the capacitance of the material and, hence, the moisture content of the material can be measured. Numerous commercial sensors utilizing TDR are available, most of which are targeted to agricultural applications. The probes are typically long to provide a sufficient travel time for the signal, and the measurement of moisture is averaged over the length of the probe. Localized measurements would require a smaller probe, but the resolution of the sensor may not be as great because the signal-to-noise ratio may be small with the short travel time of the pulse. Flanders and Yankielun (1997) used this technique to detect moisture in roofs but did not obtain discrete measurements of the moisture content. Discrete values of moisture content in wheat samples were obtained by Hamid (1992). The benefits of such an instrument are the low cost and simplicity of the measurement device. The disadvantages include the size of the sensor and the difficulty in obtaining localized measurements.

Infrared Techniques

Infrared techniques have commonly been used to detect moisture accumulation in walls and roofs as well as thermal gaps in a building envelope. For moisture detection, these techniques typically rely on the change in thermal capacity of a material with water content as the indicator of moisture. Tobiasson et al. (1977) and Korhonen and Tobiasson (1978) describe one such roof moisture survey that was undertaken to detect the presence of water rather than obtain quantitative values of the moisture content. An infrared camera was used at night to detect any thermal anomalies in the roof. Wet materials in the roof remain at a higher temperature longer because of the thermal capacity of the water. This elevated temperature can be detected using an infrared camera. Such a technique is not applicable to in situ measurements unless the data acquisition from the camera is automated. Additionally, surface features of the wall or roof seriously affect the signal, making discrete measurement of moisture content of the materials on the inside of the wall difficult.

An alternative use of infrared radiation that more directly measures the moisture content of a material is used extensively in various process industries. Water molecules selectively absorb three distinct wavelengths in the infrared region of the electromagnetic spectrum—$2.738 \cdot 10^{-7}$ m, $6.270 \cdot 10^{-7}$ m, and $2.662 \cdot 10^{-7}$ m (Wang 2000). By shining light on a solid and measuring the reflected light, one can determine the amount of moisture in the material. The intensity of the light at the three particular wavelengths can be correlated to the moisture content of the material. For thin materials, one may be able to measure the amount of light transmitted by the material to detect the moisture content, but such an arrangement would necessitate sensors on two sides of the specimen. The infrared reflectance technique allows a noncontact measurement of moisture content, and many commercial products are available for use in process industries.

The major disadvantage of infrared reflectance is the fact that it is a surface measurement, and surface effects could interfere with results. No information can be obtained about the moisture content below the surface without boring into the specimen. Additionally, if the surface changes over time, the optical properties of that surface could be affected, leading to drift in the measurements. This problem is inherent in many intensity-based optical measurements. One way to work around this problem is to analyze the attenuation of both a wavelength that is absorbed by water and one that is not. The attenuation of the wavelength not absorbed by water will provide an estimate of surface effects that are not related to moisture and can be used to adjust the measurement from the wavelength that is tuned to water molecules.

No attempts to use infrared reflectance for making in situ measurements inside building cavities have been found in the literature. It may be possible to use optical fiber to deliver light to a spot inside a wall and to use the same fiber to detect the reflected light. The reflected light could be analyzed to yield a measure of moisture content. To obtain a sufficient amount of light, however, a bundle of fibers is needed since the intensity from a single strand is currently insufficient for detection. Additionally, special fiber is needed that allows infrared light to pass without unwanted attenuation. If this technique were to become viable for in situ measurement in building cavities, techniques to multiplex many sensors would need to be developed to minimize the number of light sources and detectors needed, and techniques to deliver light efficiently to and from the measurement location would need to be investigated.

Microwave

Microwaves could be classified as a technique that utilizes the change in dielectric properties of the material to determine the moisture content. The two methods have been separated in this discussion because of differences in the specifics of operation. One way in which microwaves could be used to determine the moisture content is to transmit these waves through a material and sense the attenuation or phase shift of the wave on the other side of the material. Such a configuration would require sensors on both sides of the material of interest. A better method for making in situ measurements involves the construction of a microwave resonator. By including this resonator in a circuit, one can determine the moisture content because the dielectric constant of the surrounding material affects the resonance of the microwaves. The dielectric properties of the material affect both the phase of the resonance and the input resistance of the circuit at resonance. If the resonator is made small enough, the measurement of moisture content could be localized. While no evidence is found of this technique being used to measure the moisture content of building envelopes, numerous researchers have developed these devices to measure the moisture content of such materials as sand, soil, and agricultural products (Abegaonkar et al. 1999; bin Khalid and Hua 1998; Lasri et al. 1991; Nakayama 1995; Nelson et al. 1992; Parchomchuk et al. 1990; Yogi et al. 1998, 1999).

The advantage of this technique is the accuracy and the affordability of the parts to make the circuits. Researchers have claimed an accuracy as low as 0.1%; thorough explanation of those claims, however, was not provided. A major drawback is the difficulty in constructing a resonator. Significant knowledge of the propagation and reflection of microwaves within a chamber is needed to set up the resonant waves. As with other capacitance-based sensors, a microwave resonator will provide a measure over an unknown distance into the material. If the sensor can be made sufficiently small, though, the size of the measured location can be decreased.

Proton Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) is a technique that is commonly used in benchtop applications. NMR has the ability to detect a wide range of constituents, including water in different states. A magnetic field is first applied to the specimen. When the field is released, hydrogen nuclei in the material gradually return to their ground-level energy state. The energy released by these atoms during decay is monitored, and the time for the decay is an indication of the amount of hydrogen. Since each water molecule consists of two hydrogen atoms, the amount of hydrogen in the sample is closely related to the amount of water. This technique provides accurate estimations of the moisture content of a material with relatively little noise.

NMR has been used to detect moisture content in agricultural products such as wheat, corn, and other grains (Brusewitz and Stone 1987; Cho and Chung 1997; Tollner and Hung 1992). Tollner and Hung provide a particularly effective introduction to the physics behind the measurements. Applications have also been found in the ceramics processing industry. In situ applications, however, would be difficult in a building due to the size of the instruments. One manufacturer claims to have miniaturized the sensors, but they are still approximately 85 mm in diameter with a depth of 53 mm. The other disadvantage of this technique is the high cost of the instruments. The components themselves are quite expensive, but decreases in cost with mass production are not foreseen in the future.

Nuclear Scattering

Scattering of neutrons has also been used to detect the presence of hydrogen atoms in a sample. Knab et al. (1981) reviewed this technique for roof surveys, and Schaack (2000) discusses a typical gauge that is used for roof surveys. A radioactive source emits neutrons that are scattered by hydrogen nuclei. The number of neutrons that are captured by a detector indicates the level of water in the specimen. Despite the promise of the concept, Link and Miller (1980) suggest that this instrument can detect the presence of water in a roof, but it is not sufficient for measuring discrete levels of moisture content. Knab et al., however, had more success with measuring the degree of wetness. This technique has also been used to detect moisture in toxic waste by Watson et al. (1997).

A related technique is the one discussed by Couvillion et al. (1992). In this work, the authors transmitted gamma rays through a specimen of insulation and determined the moisture content by measuring the percentage of radiation passing through the specimen. Hydrogen atoms intercept the gamma rays, so this method once again determines the amount of hydrogen in the specimen. This method is appropriate for online studies, but application of a transmission technique as an in situ tool is challenging. Additionally, the use of radiation as a moisture detector in a building raises safety issues.

HUMIDITY SENSORS AS MOISTURE CONTENT SENSORS

Owing to the difficulty in measuring moisture content, humidity measurement has been used in place of direct moisture content measurement. Literature discussing humidity sensors is extensive, and a full discussion of all techniques is beyond the scope of this paper. Huang (1991), Wiederhold (1998), and Roveti and Soleyn (1999) provide excellent surveys of typical techniques to measure humidity. Some of these techniques include dew-point hygrometers, polymers with electrical properties that vary as moisture is absorbed, sling psychrometers, infrared and ultraviolet hygrometers, electrolytic hygrometers, piezoelectric sensors, saturated salt sensors, and surface acoustical wave sensors. For use as an in situ sensor in a building envelope, sensors that are small and that can be operated with little human intervention are the best candidates. Among the popular methods, polymer sensors are the most applicable to in situ studies of moisture in walls. These sensors are typically capacitance-based sensors in which a polymer that absorbs moisture is sandwiched between two electrodes. The capacitance of that polymer film depends on the humidity of the surrounding air and can be measured to obtain an indication of the humidity. Such sensors can be made rather small, and accuracies of ±1% have been reported in product literature. As with most humidity sensors, problems often occur in condensing atmospheres. For those situations where condensation can be expected, these sensors may be irreversibly damaged. Unfortunately, those situations are of greatest interest in studies of the building envelope. These sensors appear to be susceptible to drift, so recalibration is often necessary to maintain accuracy.

Several researchers (Hosni et al. 1999; Cunningham 1999) have embedded humidity sensors into a small cavity in a material and have used the sorption isotherms to translate the humidity readings into a measure of the moisture content in the region surrounding that cavity. This method permits one to use off-the-shelf humidity sensors that are small to obtain a moisture content reading. Because humidity is such a widely measured parameter, a tremendous range of options exists for making these measurements, and a great deal of expertise exists to create effective sensors. An advantage of the use of humidity sensors over some of the techniques previously mentioned is that their values do not depend upon the contact that the sensor makes with the solid material. Measurement of water in air is much easier than in solids because of the diffusion of the moisture to the sensor. Developments have also been made to manufacture small sensors that are appropriate for building science applications. These sensors typically provide an easy way to gauge moisture problems in buildings.

This method does have several drawbacks, however. First, as mentioned previously, many of these humidity sensors break down when the relative humidity approaches 100%. In many instances, these conditions lie in the regimes of interest. These sensors also require temperature correction, and care must be taken when temperature changes in the environment surrounding the sensor at a rate such that a temperature lag exists at the sensor. Another drawback is the use of the sorption isotherm to translate from relative humidity to moisture content. This relationship is not well established for a wide range of materials, and significant uncertainty can exist in those functions that are known. The functional form of the relationship also presents problems when trying to obtain a measurement of the moisture content. Figure 1 displays sorption isotherms for several building materials. Near RH = 50%, an error of 1% in RH would not cause a significant error in the moisture content because the curve is flat. At high RH, however, the same error in RH would lead to a substantial error in the moisture content given the large slope in that region. Once again, since the high moisture content region is often the area of interest, the use of sorption isotherms to obtain the moisture content could lead to significant errors in the readings. Another problem with using humidity sensors to obtain the moisture content lies in the fact that hysteresis leads to a range of valid moisture contents for each relative humidity. It may be necessary to incorporate adjustments in measurements to account for the direction in which the moisture content has been reached. One last drawback arises from the original definition of the sorption isotherm. This curve is obtained by allowing a material to reach equilibrium with an environment of known humidity. Depending on the material, this process could take a significant amount of time. There is no guarantee, therefore, that the material surrounding the humidity sensor has reached equilibrium with air measured by the sensor. The time constant of the humidity change is significantly smaller than that of the moisture content change. The chamber must be sealed tightly for the readings to have any significant meaning. Until a greater understanding of the transient nature of the sorption isotherms is obtained, translation from RH sensors to moisture content will have an added degree of uncertainty. It is believed, however, that knowledge of the transient nature of the sorption isotherms could lead to better predictions of moisture content from transient humidity measurements.

CONCLUSION

The state of the art in moisture measurement in building envelopes has changed little over the past twenty years. Electrical resistance measurements along with measurements of the capacitance of the material are the dominant means of determining the moisture content within a wall. While many technologies are used in other industries for measuring the moisture content of various solid substances, no major effort has been undertaken to find better methods for measuring the moisture in buildings. Conventional methods may be sufficient for many applications, but advances in modeling the moisture transfer in buildings have spurred the need for more accurate sensors.

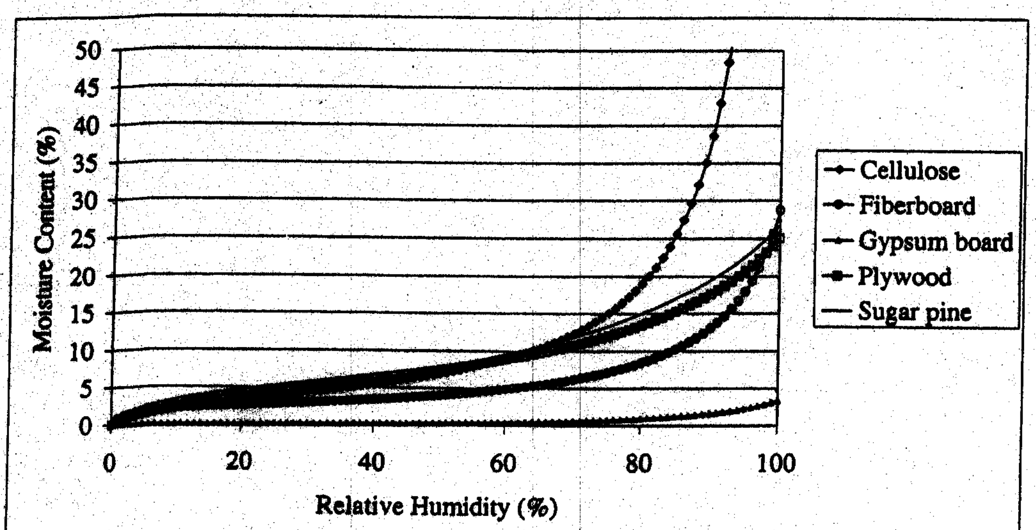

Figure 1 Sorption isotherms for selected materials.

The technologies used in other industries may provide ideas for innovative sensors for the building science community. The challenge in adopting these methods will be in packaging the sensor so that it can be installed with little effort, cost, and destruction to the structure. The continued development of sensors on integrated circuits could likely lead to a sensor that would meet the requirements of size and cost. Such sensors may be able to incorporate the techniques developed for other industries on a much smaller scale package. Integration of wireless communication technology would also benefit the building science community by easing installation of the sensors in buildings. While the use of humidity sensors to detect moisture problems has promise, direct measurement of the moisture content within solids should not be neglected. To achieve such measurements, the various techniques that have been discussed here may play a pivotal role in sensors that are accurate, reliable, and easily installed.

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